A SURVEY OF HIGH ALTITUDE BRUSH PROBLEMS

ROBERT E. MORRIS

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A SURVEY OF HIGH ALTITUDE BRUSH PROBLEMS

By

Robert E. Morris

Lieutenant, United States Navy

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P R E F A C E

The purpose of this paper is to attempt to bring together from a wide variety of sources the predominant theories pertaining to the problems encountered using carbon collectors operating under the conditions found in modern aircraft, to present some of the attempts that have been made to arrive at satisfactory solutions, and to suggest another line of research that due to time limitations imposed by the moving of the U. S. Naval Postgraduate School from Annapolis, Md. to Monterey, Calif., the writer was not able to pursue himself.

Monterey, California
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R. E. Morris

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A SURVEY OF HIGH ALTITUDE BRUSH PROBLEMS

The difficulties encountered in obtaining satisfactory current collection from electrical rotating equipment operating over the wide range of conditions peculiar to machines that are a part of military aircraft have been acute enough in the past decade to cause considerable concern to the Air Force, Navy, and many of the large electrical equipment manufacturing companies.

There are two main requirements to be met by current collectors. First, they must be capable of carrying heavy current densities without excessive heating, excessive voltage drop across the collector, and, in the case of D. C. machines, provide for the sparkless commutation. Second, the life of these collectors should be such that under the specified operating conditions costly and time consuming replacements are avoided.

For stationary machinery operating year after year in approximately the same environment ordinary carbon brushes have served very satisfactorily as current collectors for both A. C. and D. C. machines. The term ordinary as it is used here does not mean that any carbon brush will be satisfactory for any machine, but, for a given machine after it has been designed, brushes can be fitted by a process of trial and error that will

give satisfactory commutation. These trial brushes may vary as to composition, specific resistance, and to the spring pressure used to hold the brush to the commutator.

The brushes for aircraft equipment must operate in ambient temperatures varying from -73 degrees to +100 degrees Fahrenheit at altitudes varying from sea level to 50,000 feet, with rated current densities of about 200 amperes per square inch for generators, and about 100 amperes per square inch for motors. Modern D. C. aircraft generators are designed to receive cooling air from external sources with a minimum in flight total head drop across the generator of 6 inches H_2O, while most motors are totally enclosed. These requirement mean wide variations in mass of cooling air, amount of oxygen, percentage of water vapor, and percentage of contaminants present. All of these factors play important parts in the life and efficiency of carbon brushes.

Satisfactory brush life as used herafter is defined as a brush that after being properly run in will not wear more than 1/4 of an inch operating at rated current density at either sea level or at 50,000 feet in 1000 hours. Rated current density at 50,000 feet is taken as 75% of rated current density at sea level.(9) This derating at altitude is necessary for electrical equipment because the effect of the reduced mass of the cooling air is greater than the effect of the much lower ambient temperatures.

The earliest reference to the effects of humidity on brush life that has come to the attention of this author was a report on the wear of slip ring brushes of a large alternator during a cold dry winter. This report[5] indicated that whenever the moisture content of the air dropped below 1.25 grains of water vapor per cubic foot of air, carbon brushes could be expected to wear very rapidly. Further tests run during 1934 and 1935[4] determined the critical moisture content for safe operation of carbon brushes to be about 2 grains per cubic foot. No mention was made of the types of carbon brushes used in these tests.

The first reference to the failure of aircraft brushes in this country was a report of failure of brushes on slip rings controlling the pitch of the Curtiss Electric Propeller in 1940.[11] In the German literature reference is made to a case of rapid wear occurring at an altitude of 15,000 feet as early as 1935.[18] During 1943, according to Mr. Finnison of Wright Field, D. C. generator brushes were failing on high alititude bombers before one mission could be completed over Germany, and pursuit planes were needing brush replacements every two or three missions. Since that time with increasing electrical loads and the advent of jet aircraft the brush wear problem has been compounded many times.

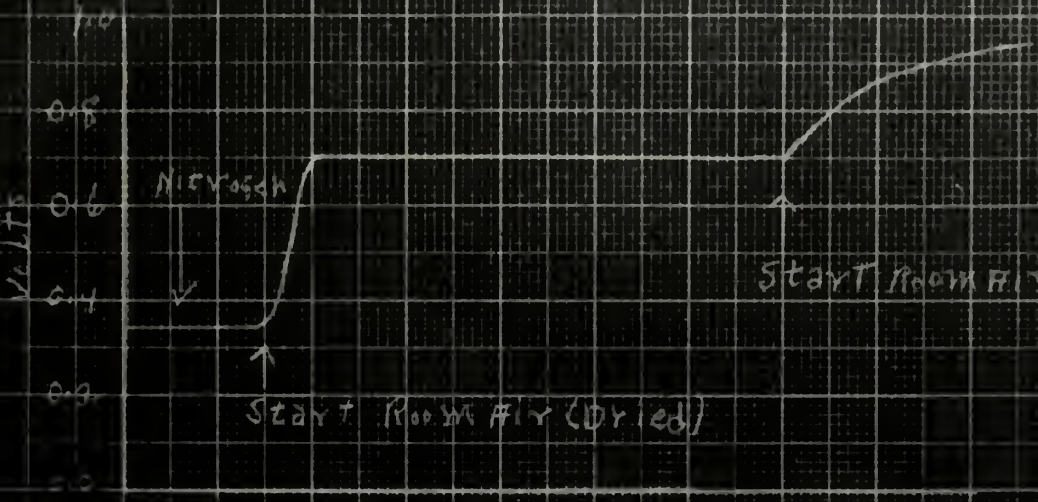
Several theories as to the cause of this brush wear have been presented. Two of the most prominent theories will be presented here.

It has long been known that the copper oxide film has been essential for sparkless commutation [1] and it has been noted that with the disappearance of this film brushes would commence to wear rapidly and commence to dust. That the disappearance of this film was often coincident with low humidity was also noted. The exact composition of this film was for a long period of time in question. However, in 1944, one investigator [16] was able to remove sections of this film and by micro-chemistry to analyze the constituents. It was found that the average film consisted of two strata. The strata next to the metal consisted of Cu_2O (cuprous oxide, a semi-conductor) average thickness about 210 Angstroms. On top of this was a strata of graphite averaging 300 Angstroms thick. Contained in this film was foreign contaminants to the extent of 15.1%. These contaminants were SiO_2, Al_2O_3, Fe_2O_3, and CaO. Origin of the contaminants was unexplained.

One theory [5] that has been proposed to explain many of the phenomena of sliding friction and current conduction that has been proposed is that the copper oxide film acts as a lubricant between the sliding brush and the metallic conductor. The current is conducted by a puncture of this

film with the total area of the conducting path very small compared to the area of the brush. Due to the high current densities of these conducting paths the local temperature is extremely high, and at these temperatures the copper oxide is reduced to metallic copper and carbon monoxide. As these minute spots rotate from under the brush, the average temperature of the commutator is sufficient to rebuild this film. The action of the water vapor has been explained as that of a chemical catalyst that increases the rate of oxidation.

There is a considerable evidence that appears to support such a theory. Tests completed in 1936 to obtain the electrical characteristics of carbon brushes indicate that the voltage drop across the brush contacts is related to the thickness of the copper oxide film.(1) For example, a clean slip ring, i. e., no visible oxide film, was operated in nitrogen atmosphere and the voltage drop across the contacts was a constant small value as shown in Fig. 1. Upon admitting dry air, the voltage drop increased to a new level, and upon admitting room air the voltage drop again increased and leveled out at a higher level. Another attempt was made using oxygen atmospheres first. The results are indicated in Fig. 2. Fig. 3 gives the result for a

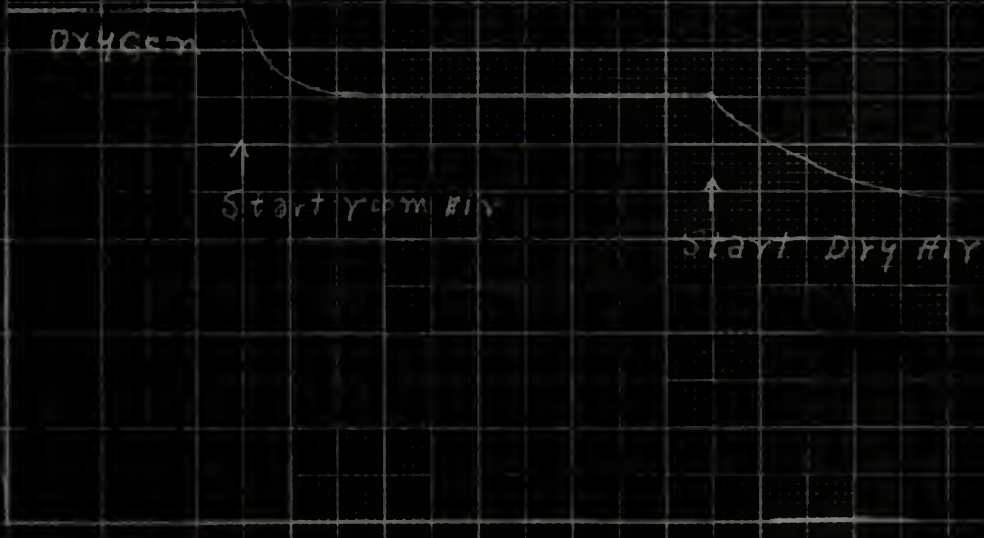


← 15 → Minutes

time →

Fig. 1

Voltage Drop in Atmosphere



time →

Fig. 2

Voltage Drop vs Atmosphere

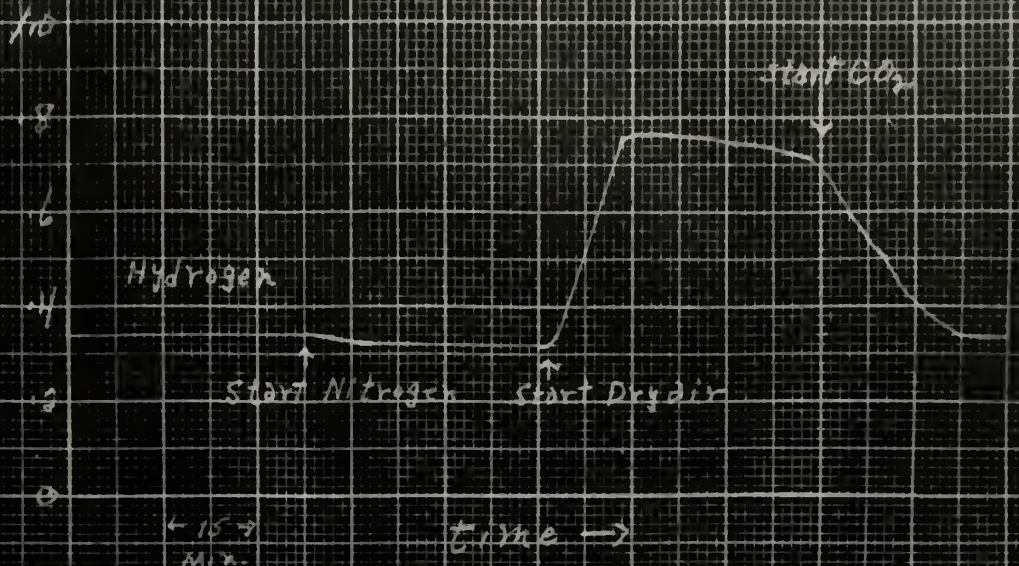


Fig 3

Voltage Drop Vs Atmosphere

Figures 1, 2, and 3, represent the voltage drop across the positive brush of a slip ring operating in different atmospheres. Current density maintained at 40 amperes per square inch. Peripheral velocity 7.65 feet per second.

The above figures are taken from Mr. Baker's article Sliding Contacts, Electrical Characteristics, AIEE Transactions, 1936, Vol. 55, page 98. It was not the writer's intention to copy the curves exactly as they were made with a drum recorder. The above plots are approximate average values that show the trend.

clean slip ring run first in hydrogen, then nitrogen, dry air, then carbon dioxide. The important things to note from these tests is that the voltage drop increases with oxygen content and also that water vapor in the atmosphere increases the voltage drop across the brushes. Independent tests not shown here have shown that water vapor introduced to the saturation point with the brushes operating in a nitrogen atmosphere have no noticeable effect on the voltage drop across the contacts. Another important point is the rapidity at which the contact drop decreases in the presence of a neutral (carbon dioxide) atmosphere.

As for the lubricating effect of the oxide film, there is evidence that copper oxide will act as a lubricant in metal to metal contact. (2) That this lubricating effect is carried over in the case of carbon to metal contact does not necessarily follow.

The other theory is that water vapor functions as a lubricant between the contacts and that it affects the film only indirectly in that it prevents the abrading and wearing away of the film. (17) The proponent of this theory has experimentally shown that in the absence of oxide films and oxidizing atmospheres, the addition of small quantities of water vapor has a pronounced effect on the rate of wear of carbon brushes. Partial pressures in the range of 3 to 5 m Hg. will decrease wear in proportion to the pressure. Above 5 m Hg. the wear rate is very low and independent of the pressure of the water vapor. Experiments with metal to metal

sliding contacts have shown that certain vapors including water vapor do have pronounced lubricating qualities.(13) In the tests just described there is no mention of currents being passed through the collector except before the experiment was actually started, to bake out any vapors that might have been physically adsorbed on the surfaces.

It has been shown through stereoscopic views of electron-micrographs that the surface of the graphite strata of the film is not composed of platelets oriented parallel to the surface as had long been thought, but that graphitic projections extend upwards from the surface at angles up to nearly ninety degress. The vast majority of these projections are at angles of less than 45 degrees and have an orientation determined by the direction of rotation. The investigator suggested that these microscopic projections might be the conductors and that the carbon is in reality a microscopic brush.(14)

It has been shown that carbon dust adsorbs large quantities of some gasses some of which are adsorbed chemically to fill certain valence bonds. It is believed that oxygen, hydrogen and nitrogen are chemisorbed while water vapor, N-Heptane and other vapors are physically adsorbed. . It is believed that a partial monolayer of the physically adsorbed vapor is sufficient to provide lubrication. It was also shown that the chemisorption of oxygen aids in the physical adsorption of

the water vapor.[15]

While these theories try to explain what is happening in the upper atmosphere that causes brushes to wear out, many attempts have been made to increase the operating life of brushes at high altitudes. The first thought was to try to lubricate the surfaces. Brushes were impregnated with organic lubricants and waxes. Some of these at first gave satisfactory performances at low current densities. Brush lives of the order of 250 hours were reported[11] which was very good compared to the brush life of about 4 hours for the untreated brushes. The nature of the organic compound was not disclosed. Many of the lubricants created undesireable electrical characteristics such as overheating and excessive voltage drops across the contacts. Moreover, as the current densities were increased, the organic lubricants would vaporize at the higher temperatures and the impregnated lubricant would be driven off after a very few hours of operation.

It was then suggested that certain inorganic compounds with low vapor pressures and good lubricating qualities might be used. Among the compounds tried were the oxides of lead and zinc, sulfides and probably many others that were never mentioned in the literature. Tests in 1945 on the lead oxide and zinc oxide indicated satisfactory performance at sea level. No results have been published to the knowledge of this author

for their operation at high altitudes. It must be assumed after this period of time that the high altitude tests were unsatisfactory. Molybdenum sulfide and copper sulfides were attempted but dismissed as unsatisfactory apparently because of excessive filming at low altitudes. When the film becomes too thick, it tends to flake off in small patches, roughening the surface of the commutator, which in turn causes excessive wear. Also, the thicker film causes excessive voltage drops across the contact and overheating of the commutator. Viehmann[18] mentions in his report that a successful inorganic impregnant was discovered in Germany early in the war. He neither indicates the nature of the impregnant nor does he define what he means by successful.

He further mentions an effective means of preventing brush wear by the attachment to the face of the brush, adjacent to the leading edge, a strip of white metal (Zinc, Tin or Lead) about .008" thick. Supposedly minute particles of the white metal were deposited on the surface, oxidized, and the oxide acted as an inorganic lubricant.

Concurrent with the development of the other inorganic impregnants, brushes impregnated with halogen compounds were independently developed. It was found that lead iodide would maintain the commutator film under the most adverse conditions.[8] It was proposed by Dr. Elsey that the iodide might replace the functions of the water vapor acting as a chemical catalyst favoring the oxidation of the metallic copper through an

intermediate and unstable compound of copper and iodine to form cuprous oxide. Therefore, he reasoned the other halogens should exhibit the same characteristics as the iodine. It was found that to a certain extent this was true. Since the iodide is the least stable of all the halides it was expected that it should be more efficient as a catalyst. Whether or not this is true is not known as the next report, 1950, on halide treated brushes does not mention the iodide treated brushes but concerns only lead chloride, lead fluoride, and barium fluoride treated brushes.(9) There is some mention of overfilming by lead fluoride brushes at sea level and it is suspected that some difficulty of this sort was met with the lead iodide brushes. It should be stated at this point that the above explanation of the effect of the halides does not satisfy the proponents of the water vapor lubrication theory who insist that the halide acts only as a solid lubricant between the carbon brush and the film.

In the report(9) of tests on many halide impregnated brushes in 1950, it was found that not only was the amount of the impregnating material critical, but also the type of carbon base to which the halide was added was also critical. The only brush out of a group tested that gave indications of satisfactory life at both sea level and 50,000 feet was a Stackpole Carbon Type 417 impregnated with approximately 6% BaF_2. The indicated life

of this type of brush from the wear measured during a 50 hour test was 735 hours at 50,000 feet and 750 hours at sea level. This brush is unusual in that the life expectancy is greater at high altitudes than it was at sea level. One very important fact brought out by this investigation is the relationship between current density and brush wear which is shown graphically in Fig. 4.

The German report[18] mentioned earlier claims that besides the inorganic treatment developed earlier during the war, another solution that was also completely effective in eliminating brush wear problems. This report mentions a machine designed so that the cooling air does not impinge directly on the commutator but instead the cooling air is directed over the windings and cools a shield over the commutator. The tests on this machine with the cooling air directed on the commutator gave wear rates of .6" perhour. The same machine with the cooling air bypassing the commutator had normal brush wear (.0004" per hour). Unfortunately the current densities and altitudes were not given for the tests on this machine.

After reading the results of experiments conducted with sliding contacts both metal to metal and carbon to metal, there seems no reason to doubt that water vapor and other vapors as as well in monotomic layers have excellent lubricating qualities.

Effect of Current Density on Brush Life

417BF 5.5 brushes
30 v. 300 amp. generator
50,000 ft. altitude
Comm. peripheral speed 5160 ft./min.

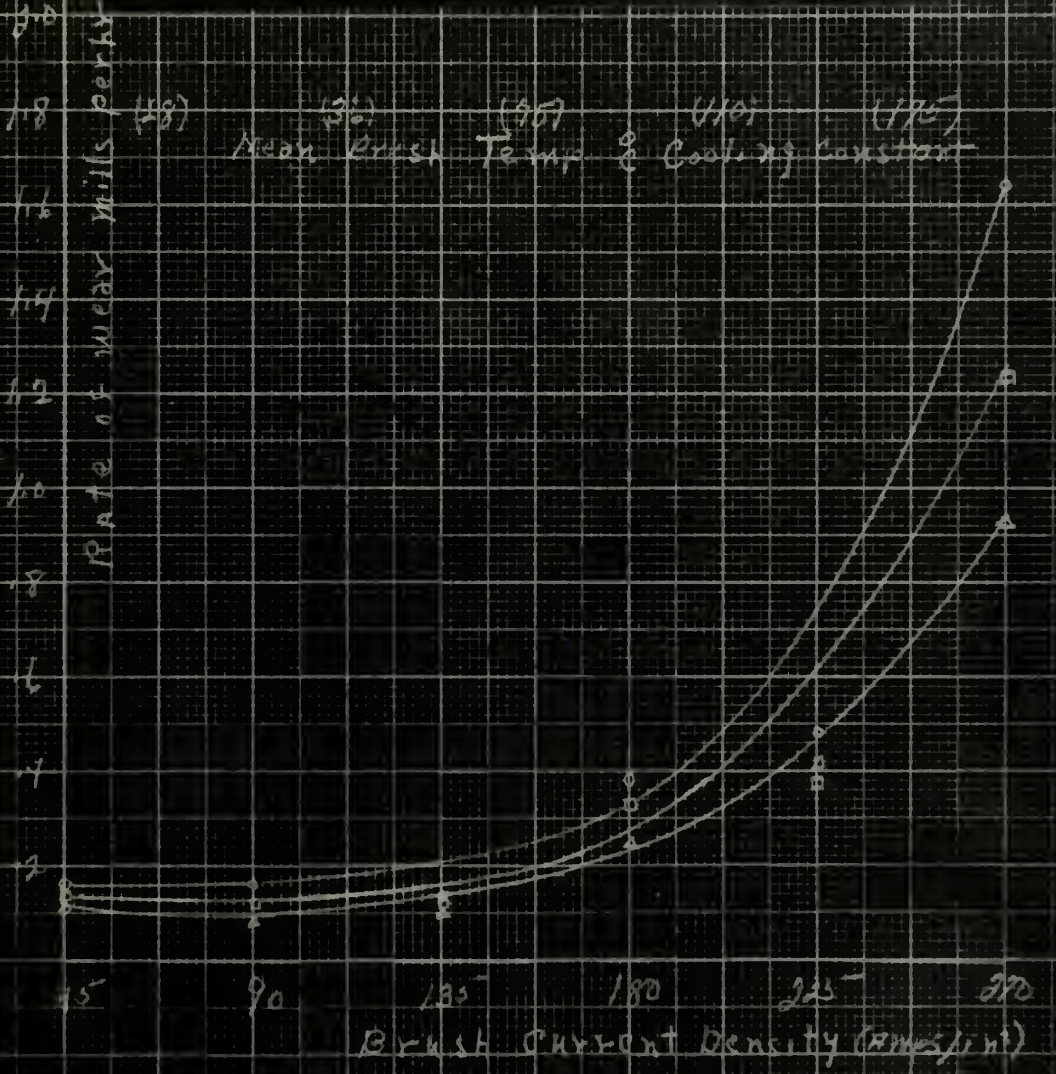


Fig. 4

There seems to be no reason to doubt that the low friction of graphite at sea level is the result of adsorption of water vapor. The elctrical characteristics of copper oxide film and many of its behaviors leave much to be explained. The dynamic film theory while not actually explaining the method of conduction across the cuprous oxide film appears to have considerable merit. Authorities agree that the voltage drop across this film is a direct function of the thickness of the film. It therefore seemed quite possible to this writer that an equilibrium condition might be set up for each current density, assuming all other factors remaining constant such as type of brush, spring pressure, and ambient atmosphere, between the reduction of the copper oxide at the high interfacial temperatures under the brush in the presence of the reducing characteristics of the carbon, and the oxidizing effect of the oxygen in the air at the average temperature of the commutator surface. Increasing the current density should shift the equilibrium in the direction of the reduction since the hot spot temperatures under the brush should increase approximately proportional to the current (this assumes that the voltage drop across the contacts remains constant) while the average temperature is also a function of the ambient air temperature. If this hypothesis is true, on sudden dumping of the load the voltage

drop across the brushes should drop considerably and then slowly build back to its original equilibrium value. That this actually happens is well known. Brush spring pressures enter into this picture in two different ways. First the pressure controls the area of contact and as such would affect the equilibrium thickness. Second, the brush pressure by friction affects the interfacial temperatures and abrasive tendencies. The composition of the brush itself could affect the reducing properties of the carbon or the oxidizing properties of the atmosphere. The effect of the composition of the atmosphere has been demonstrated by Fig's. 1, 2, and 3. Since the voltage drop necessary for successful commutation varies from machine to machine, the film thickness directly affects the commutation and the above theory could explain why changing the brush pressure or changing the type of brush will mean the difference between successful and unsuccessful commutation.

One of the first questions that must be answered to prove whether or not the above hypothesis is plausible is to attempt to find out at what temperatures carbon in the solid form will reduce the copper oxide film. In order to attempt to answer that question the experiment described in Appendix I was instituted as a form of pilot experiment. The results obtained from maintaining a copper oxide film at 500 degrees centigrade

for five hours in a neutral atmosphere was a quite noticeable reduction of the copper oxide by the carbon brush. This noticeable reduction was observed by visual comparison before and after the heat treatment. It is admitted that the above experiment was only qualitative and the apparatus did not lend itself to any degree of scientific accuracy; however, it must be remembered that this was a pilot experiment, to be followed by a more elaborate experiment which time did not permit to be carried out.

The temperature of 500 degrees centigrade was chosen for the pilot experiment because, 1., interfacial temperatures are not known but estimates have been made of temperatures of 1000 degrees centigrade (melting point of copper) and 1813 degrees centigrade[13] and , 2., limitations of equipment would not permit higher temperatures.

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APPENDIX I

A PRELIMINARY EXPERIMENT TO DETERMINE THE REDUCING EFFECTS OF ELECTROGRAPHITIC BRUSHES UPON COPPER OXIDE FILMS

The following experiment was set up to give a qualitative information of the reducing effect of carbon brushes upon copper oxide films. The actual setup of the experiment was suggested by Dr. Coonan, Chairman of the Metallurgy Department, and the necessary equipment was furnished by his department.

The samples were several strips of copper approximately 1.25" long, .5" wide, and .0625" thick. These strips were sanded flat on a conventional metallurgical sanding belt. The final finish was by hand using a fine grade of emery paper. The carbon was a piece of electrographitic brush, exact grade unknown, which was cut to a size slightly smaller than the copper strips.

The other equipment was a nichrome wire wound resistance furnace, a 3/4" silica tube about 20" long, rubber stoppers, glass tubing, rubber hose, and a supply of helium. The equipment was assembled as shown in Fig. 5.

The tests consisted of heating the furnace to various temperatures with pieces of copper inside and observing what temperatures would give the typical appearing oxide coating. It was found that a temperature of 300 degrees centigrade and

exposure of fifteen minutes gave a typical brownish film with a slight purplish cast. For the final test, a copper strip was sanded with a fine grade of emery paper, cleaned chemically by rinsing in dilute acetic acid then heated at 300 degrees for approximately 15 minutes. The previously mentioned film was obtained. The carbon block was clamped to the copper strip by means of a spring clamp made from a clock spring. The sample was replaced in the furnace with another sample of copper that had received the same cleaning treatment. The furnace was flushed several times with helium and then the clamps closed and the helium pressure brought up to 5 psi gage. The furnace temperature was brought up to 500 degrees centigrade and maintained for a period of 5 hours. The furnace was then permitted to cool with the sample under the helium atmosphere.

When the sample was removed and examined, pronounced regions were noticeable on the surface as shown in Fig. 6. Region 1, which extended well beyond the area covered by the carbon, had the same appearance that the entire copper bar had at the begin ing of the second heat treatment. Region 2, which was the region at the very edge of the carbon brush, had a dark blue-black appearance which is contributed to more complete oxidation by the room air that was not removed by the flushing. Region 3 had areas with almost pure metallic copper color with small darker islands. This is the region in which

the copper oxide and the carbon were in contact. The dark islands are believed to be the low points or the points that were not in close enough contact for the reduction to take place. The untreated piece of copper was removed in the identical condition that it had been in prior to the heat treatment.

While this experiment in itself is not conclusive, it is believed that it is sufficient to warrant further investigation.

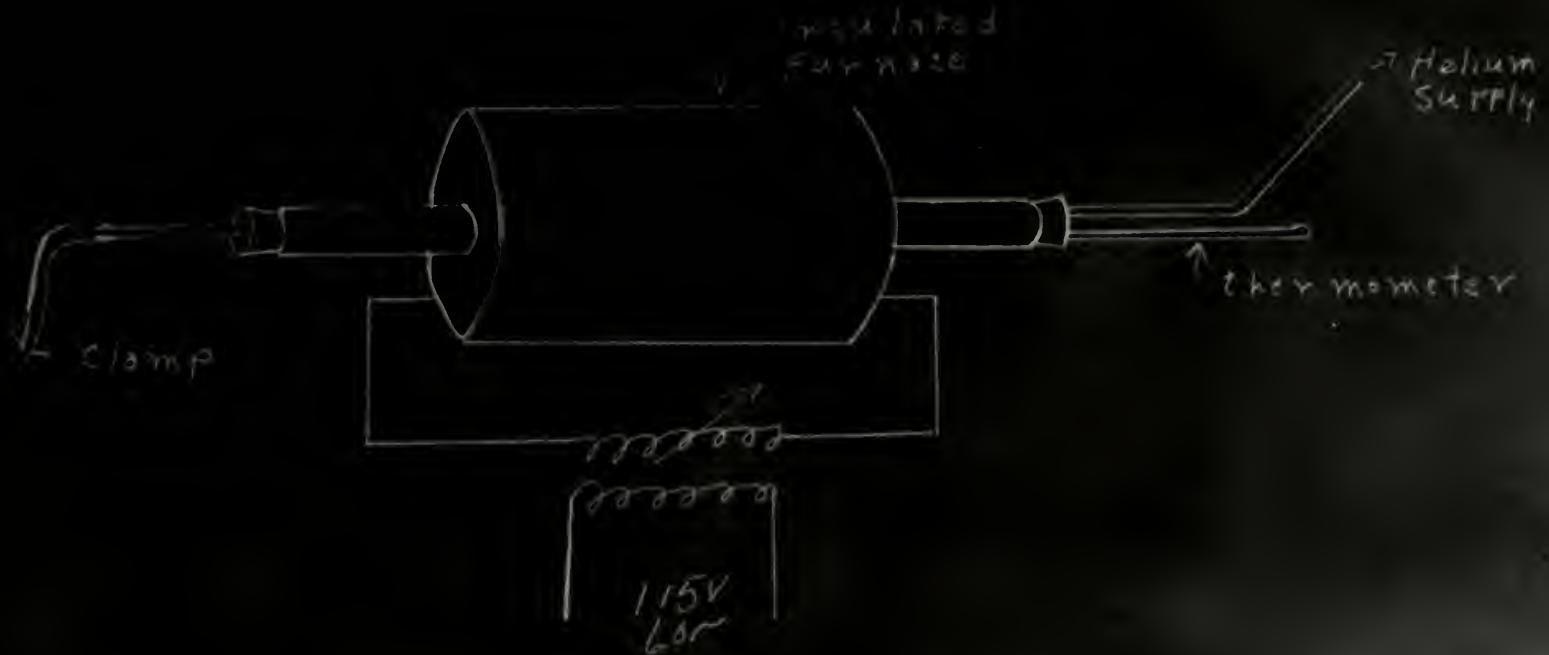

Figure 5

Schematic Diagram of Apparatus used in Determining Reducing effect of Carbon on Copper Oxide

Fig 6.

Copper strip showing effects of Carbon at 500°C

APPENDIX II

The chief criticisms that can be applied to the previous experiment are that the results are not quantitative, the methods used do not lend themselves to measurements, the temperatures at the interface are known but it is not known if they are the same temperature found on commutators, and there was no current passing through the interface.

The experiment herein proposed is designed to try to meet these objections. The equipment is shown in Fig. 7 as it is proposed to be set up. The bell jar would be flushed and evacuated several times with helium before each test. The temperatures as near as possible interface temperatures are to be measured by the thermocouple inserted in the copper bar as near the conducting surface as possible. A small area for the brush contact area should be used to prevent overloading existing facilities. At the end of each test the gasses would be pumped through a standard two stage microadsorption type carbon dioxide analyzer which should permit quantitative measurements to be made.

The equipment would permit the testing of standard brushes of varying compositions and, also, permit tests at different brush pressures. Correlation of data from these tests while not producing any specific answers to high altitude brush problems, should add to the fundamental knowledge about carbon brush contacts.

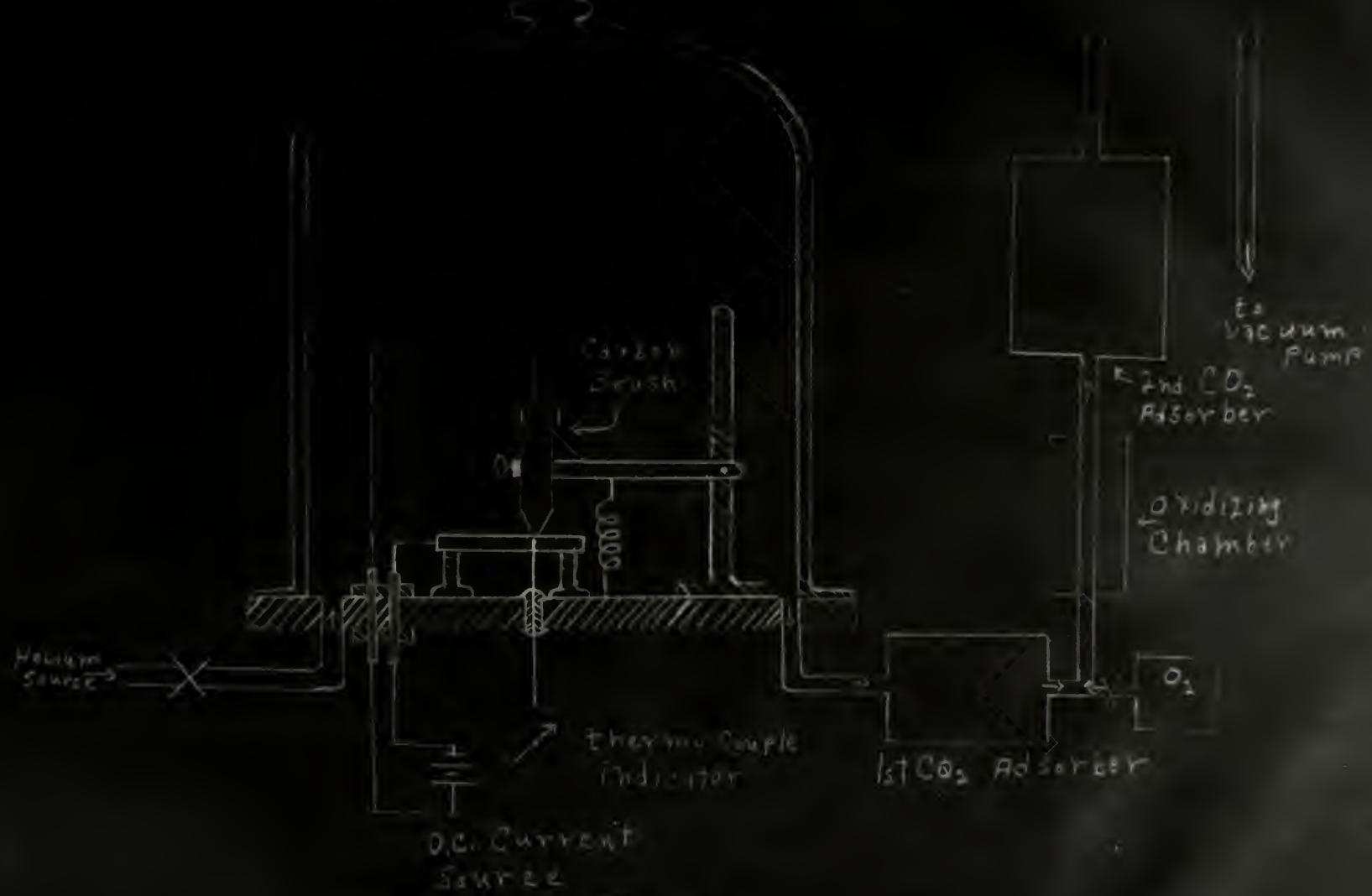

Fig 7

Schematic of Apparatus for Proposed Experiment

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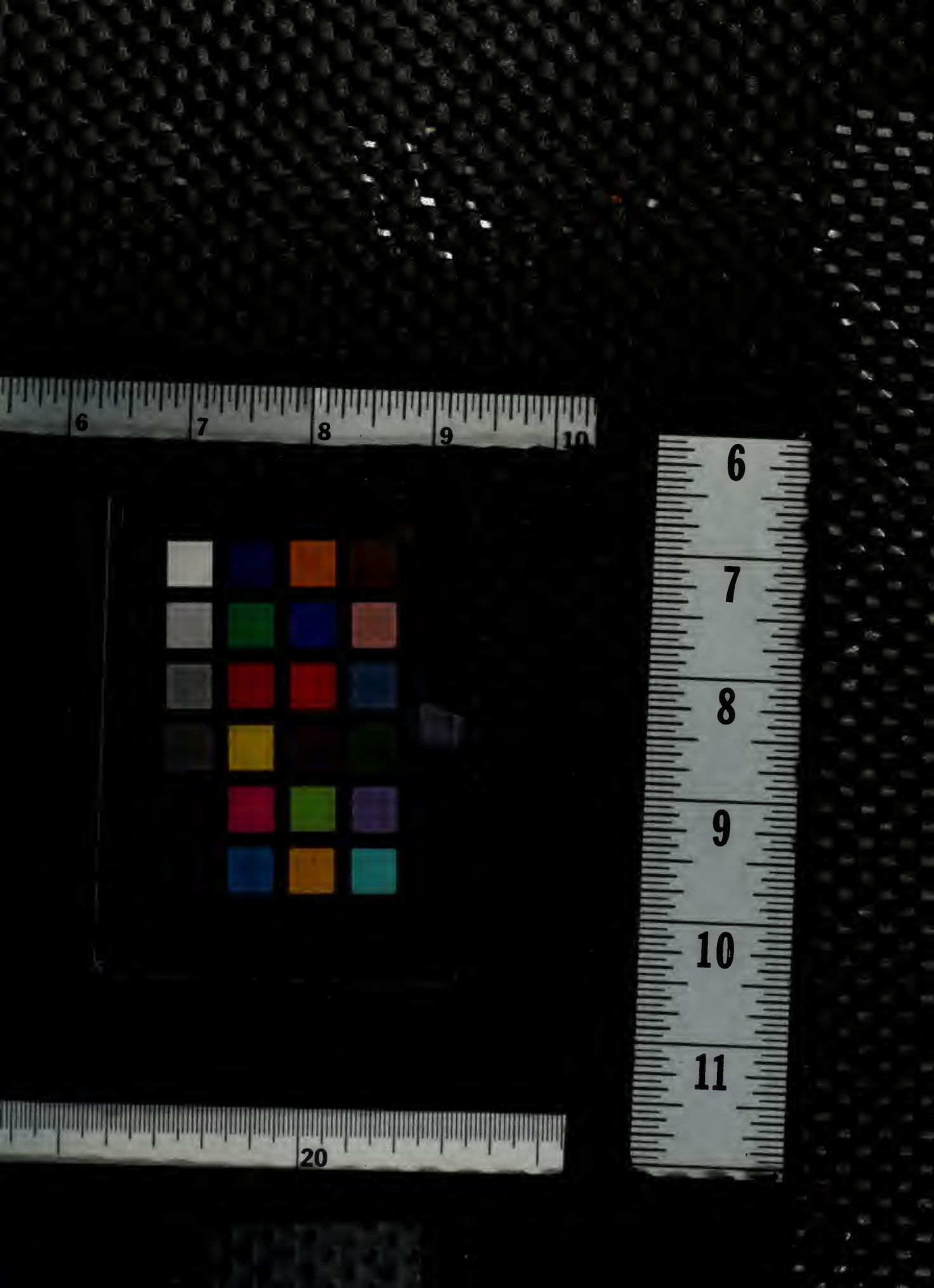
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